High-Fidelity Computational Simulation of Nonlinear Fluid-Structure Interaction Problems

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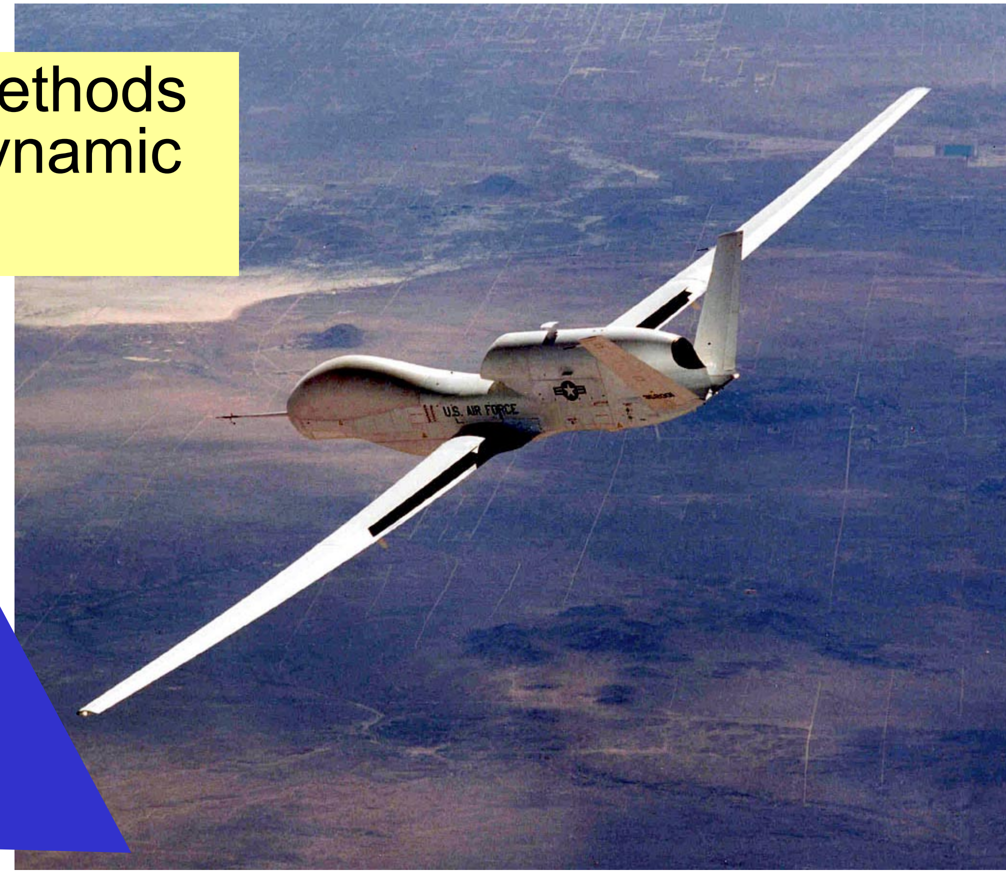
Motivation for High Fidelity Computational Techniques

Present aeroelastic design methods rely primarily on linear aerodynamic and structural models

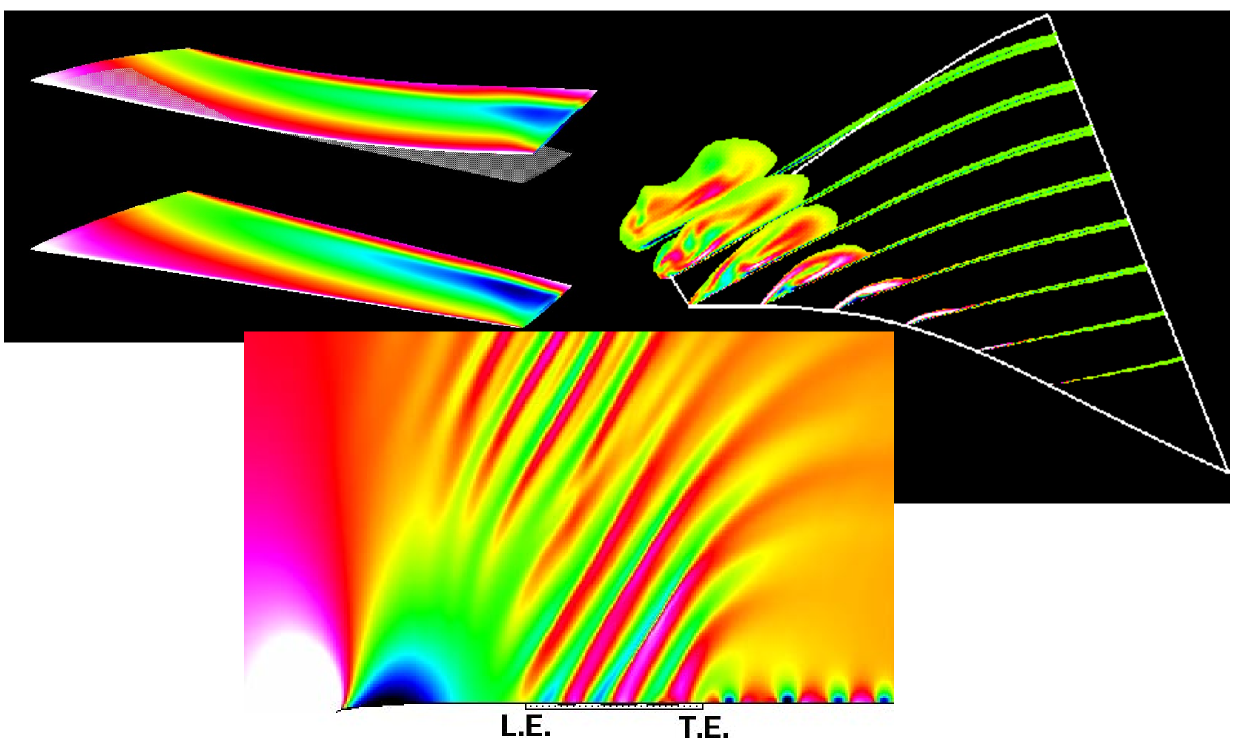


Revolutionary Concepts
Extreme Flight Conditions

Future UAV aircraft design will require the use of nonlinear aerodynamic and structural dynamic models

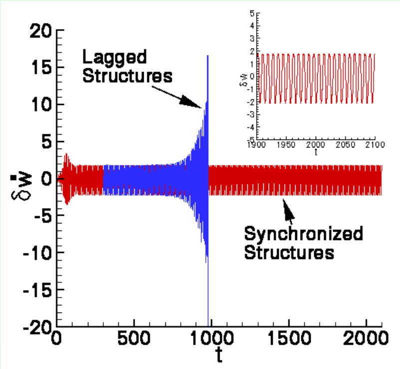
Computational Need

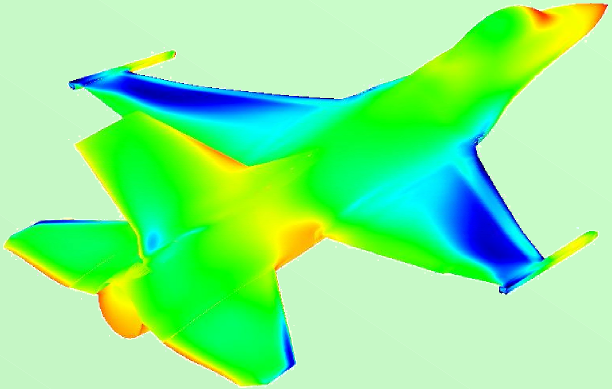
- Develop high-fidelity tools to accurately capture aeroelastic response of flexible aerospace vehicles (flutter, LCO's, buffet)
- Characterize two-way physics of fluid -structure interactions in non-linear flight regimes



Technical Challenges

- Non-linear behavior in fluids & structure
  - Structural nonlinearities may be critical
  - Transition/Turbulence may play an important role
- Dynamically deforming components
  - Impact of grid-motion induced errors
  - Efficient Grid deformation strategies
- Consistent fluid/structure interface treatment
  - Temporal synchronization
  - Loads/Deflection Transfer
- Multiple time scales of fluids & structure
  - Computational efficiency
  - Lower-order Aerodynamic models
- Aeroelastic code validition
  - Need for good, well documented aeroelastic experiments
- Coupling with additional disciplines
  - Flight Mechanics (Rigid Body Dynamics)
  - Heat Transfer (Thermal Effects)

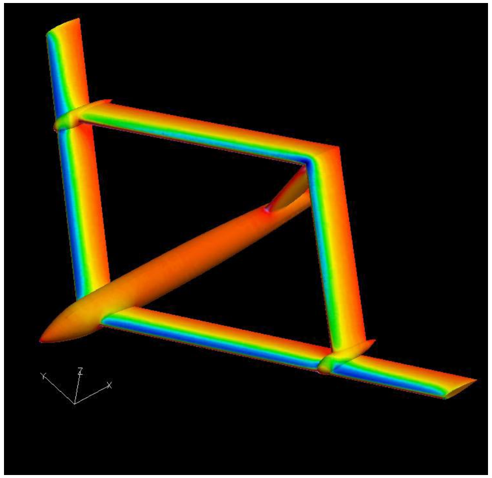




Computational Components

Aerodynamics

- Euler or Navier-Stokes
- Efficient higher-order (up to 6th order) algorithms
- Turbulence modeling (RANS, Hybrid, LES)

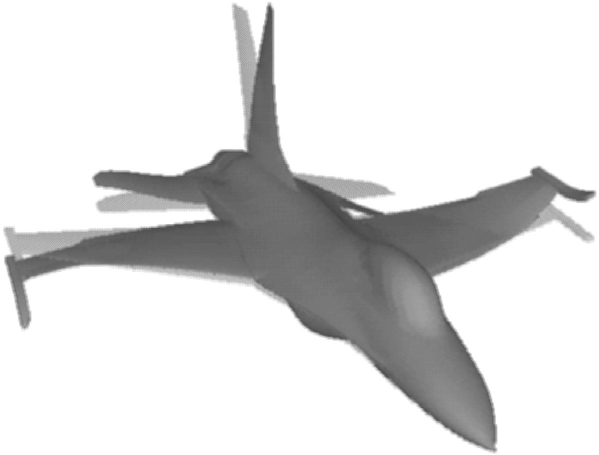


Coupling

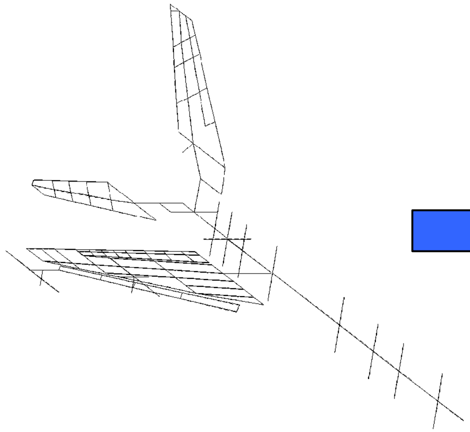
- Dynamic grid deformation
- Loads/deflections transfer
- Temporal advancement strategy

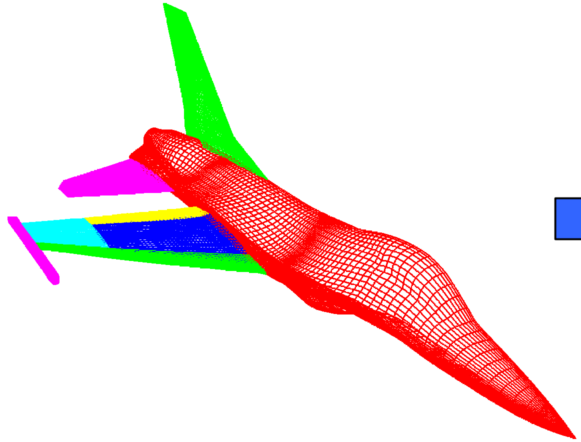
Structural Dynamics

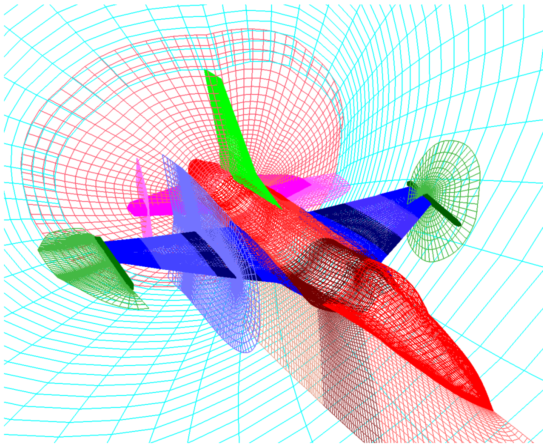
- Efficient finite-element models
- Structural nonlinearities



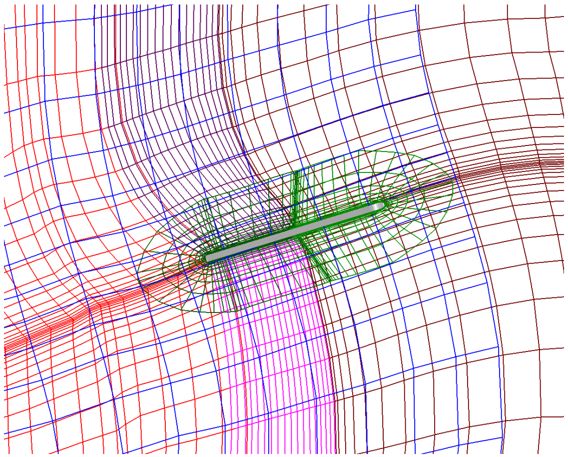
Fluid/Structure Coupling Issues
Loads/Deflection Transfer







- Accurate interpolation schemes to transfer loads/deflections
- Non-matching fluid/structure interface
- Conservation of energy
- Accurate and Robust Grid Deformation Strategies

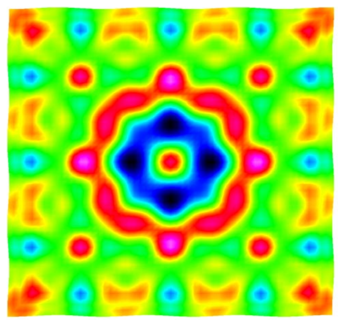


Fluid/Structure Coupling Issue
Proper Metric Treatment for Dynamic Mesh

Metric Treatment

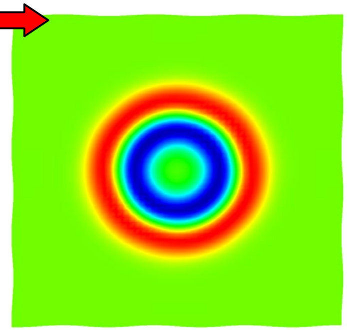
$$I_1 = (\xi_x/J)_\xi + (\eta_x/J)_\eta + (\zeta_x/J)_\zeta = 0$$

$$\begin{aligned}\xi_x/J &= y_\eta z_\zeta - y_\zeta z_\eta \\ \eta_x/J &= y_\zeta z_\xi - y_\xi z_\zeta \\ \zeta_x/J &= y_\xi z_\eta - y_\eta z_\xi\end{aligned}$$



Standard Metric Formula

$$\begin{aligned}\xi_x/J &= (y_\eta z)_\zeta - (y_\zeta z)_\eta \\ \eta_x/J &= (y_\zeta z)_\xi - (y_\xi z)_\zeta \\ \zeta_x/J &= (y_\xi z)_\eta - (y_\eta z)_\xi\end{aligned}$$



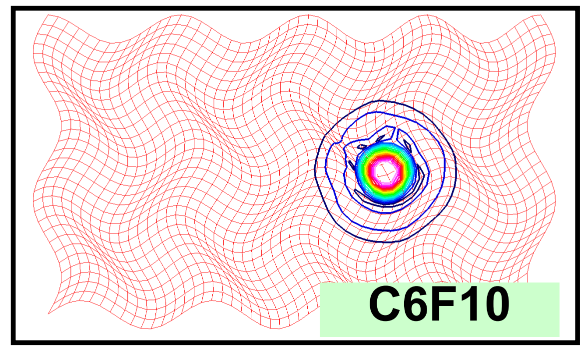
"Conservative" form

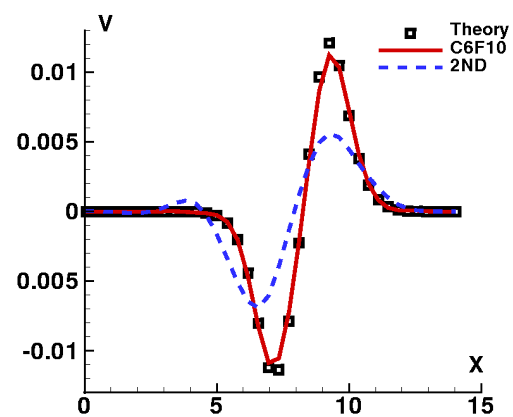
Thomas & Lombard (1979)

Geometric Conservation Law

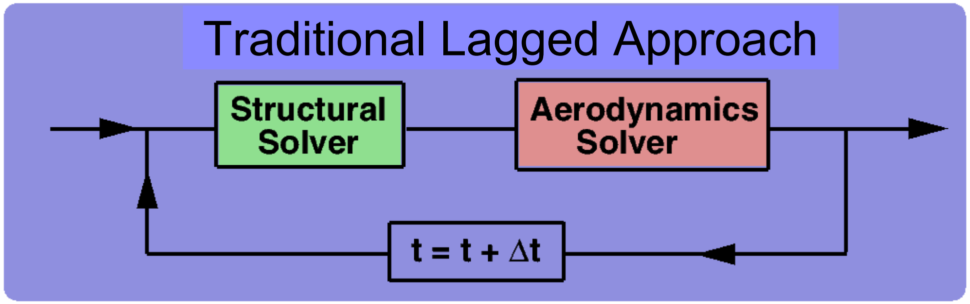
$$(\vec{U}/J)_\tau = (1/J)\vec{U}_\tau + \vec{U}(1/J)_\tau$$

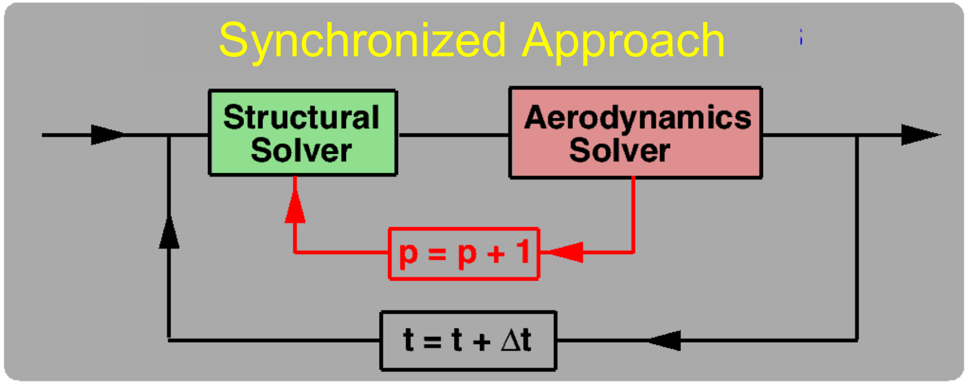
$$(1/J)_\tau = -[(\xi_t/J)_\xi + (\eta_t/J)_\eta + (\zeta_t/J)_\zeta]$$

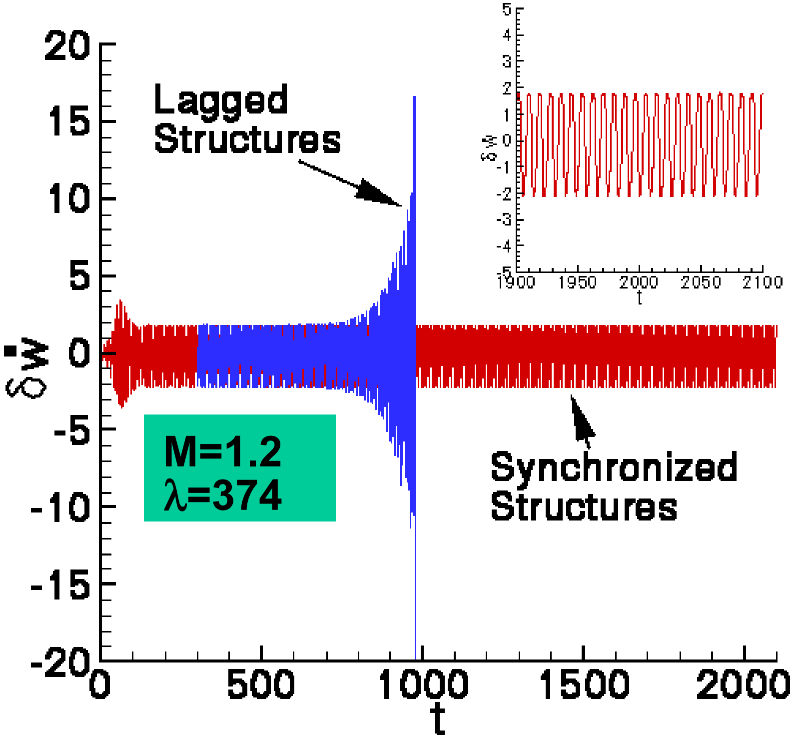




Fluid/Structure Coupling Issues
Temporal Synchronization







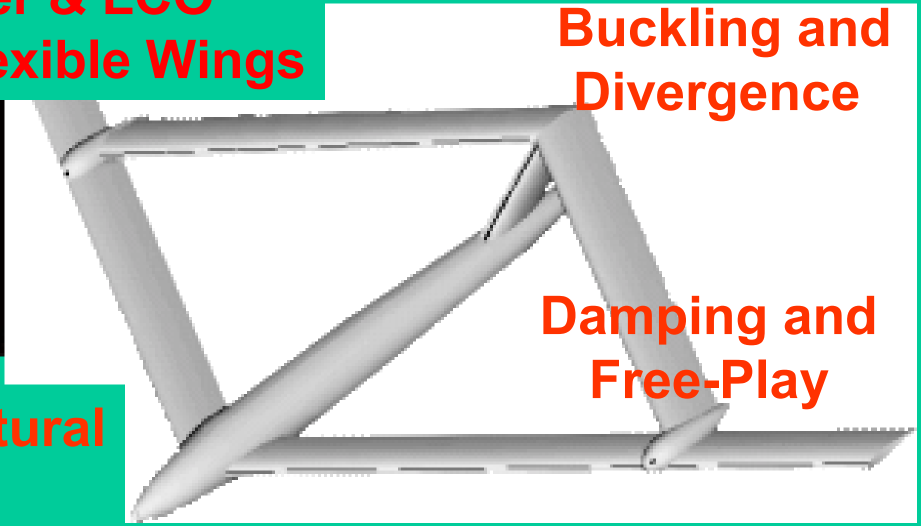
<u>**Advantages of approach :**</u>

- **Eliminates lagging errors in Fluid/Structure coupling**
- **Retains temporal accuracy for distributed solvers**
- **Retains modularity of fluids & structure methods**

Nonlinear Fluid/Structure Interaction

Vortices/
Vortex
Breakdown

Flutter & LCO
of Flexible Wings



Buckling and
Divergence

Damping and
Free-Play

Geometric Structural
Nonlinearities

Nonlinear
Material
Properties

Delta Wing Geometry

Cold-Rolled Steel

$h = 0.035$ in

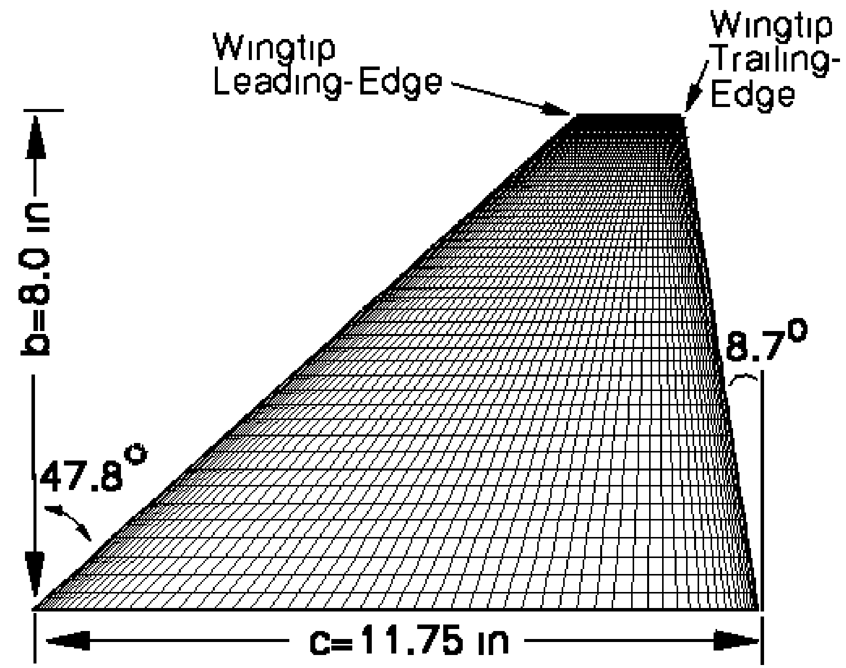
$E = 30\times10^6$ psi

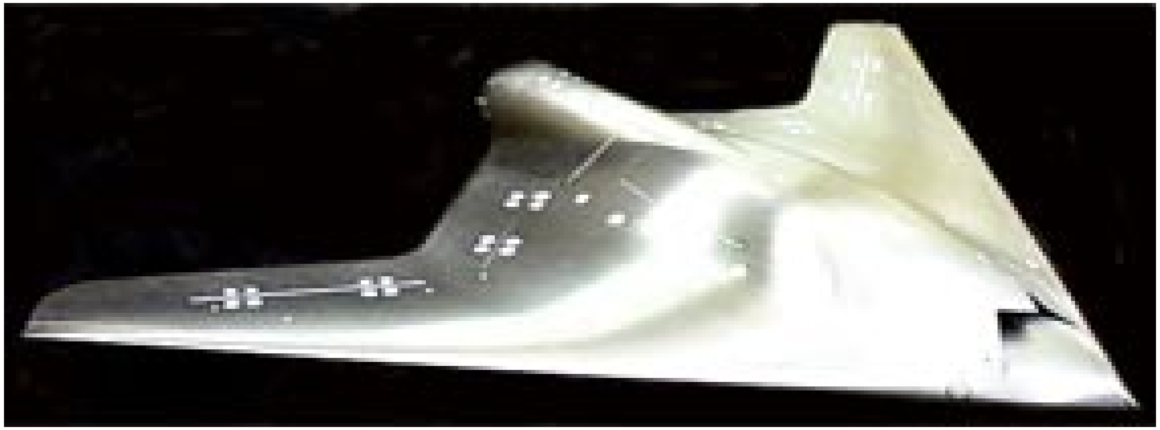
$\rho = 0.283$ lbm/in^3

$\nu = 0.25$

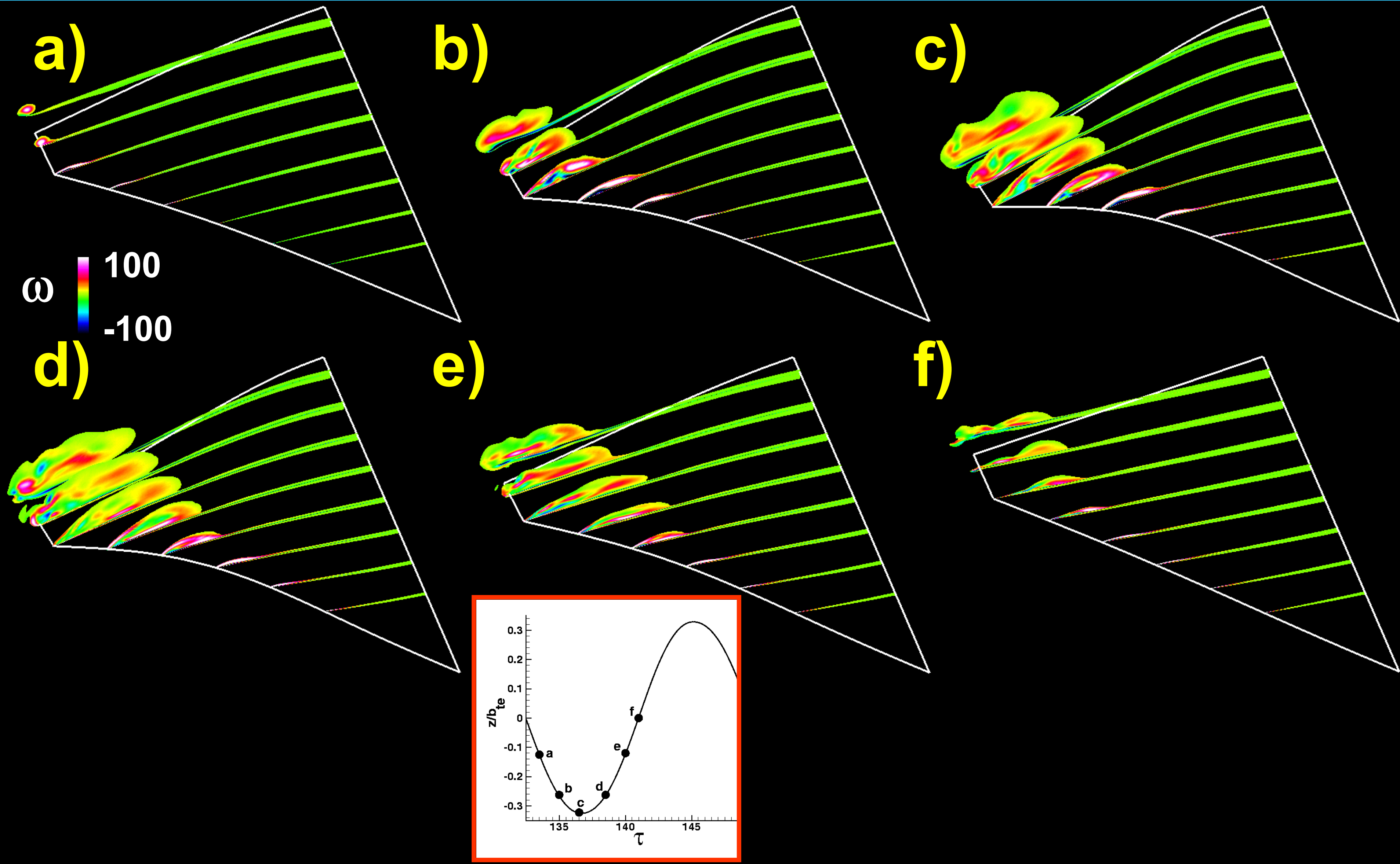
$M_\infty = 0.86 - 0.878$

$Re = 3{,}000{,}000$



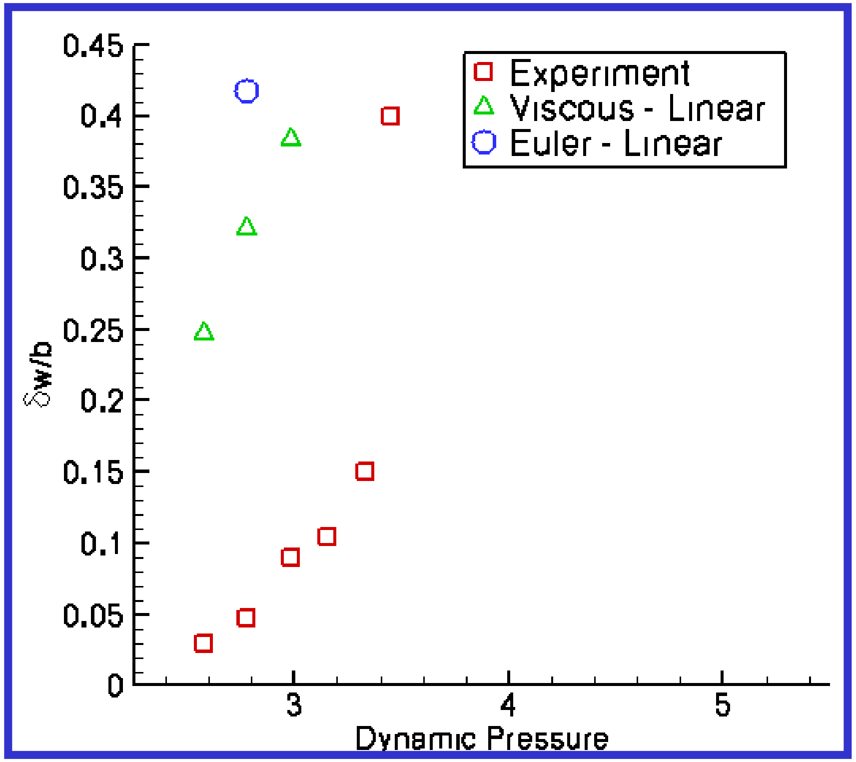


Linear Delta Wing Response

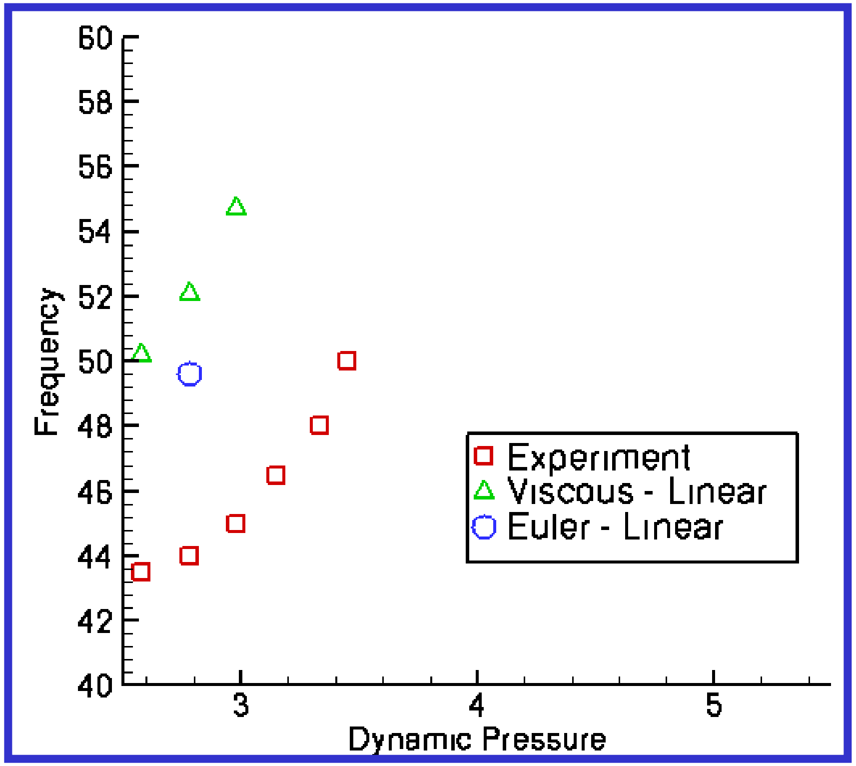


Comparison with Experiment

Amplitude

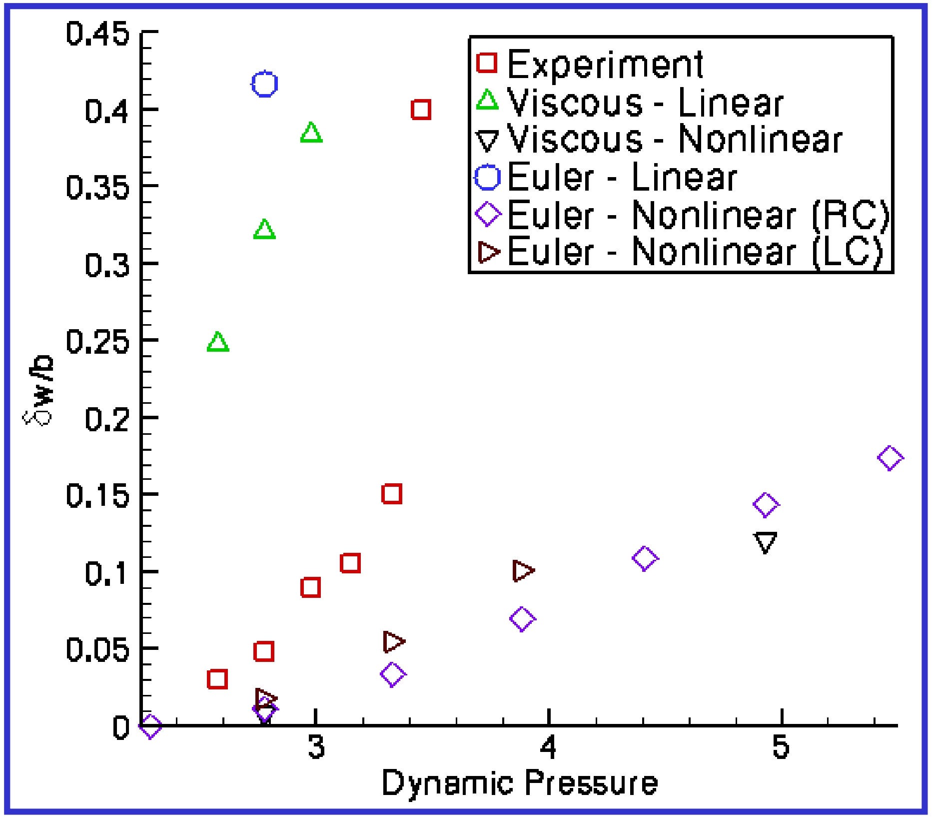


Frequency

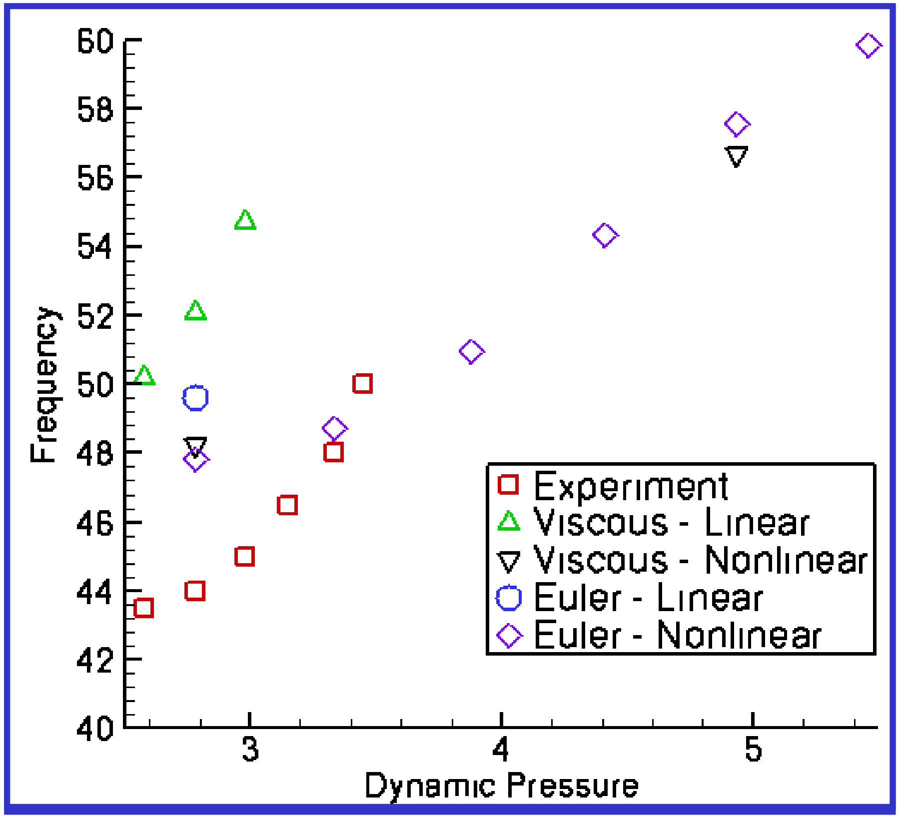


Comparison with Experiment

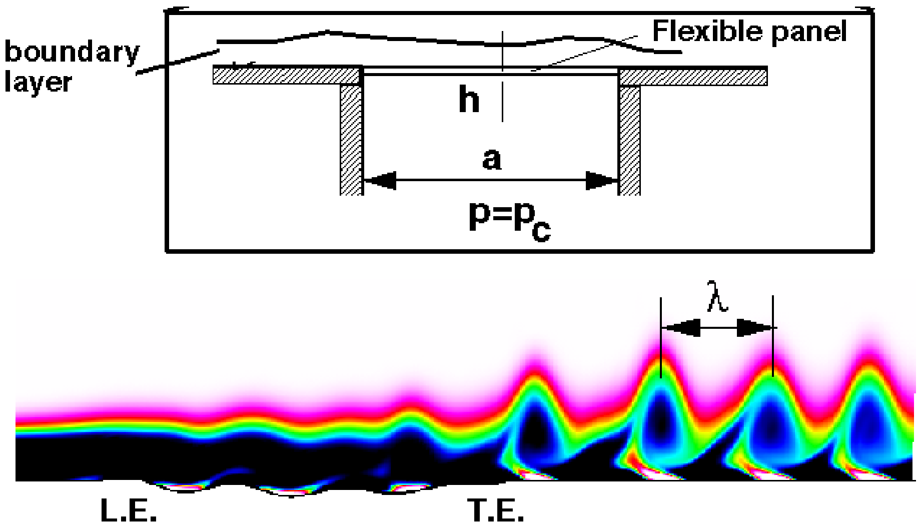
Amplitude

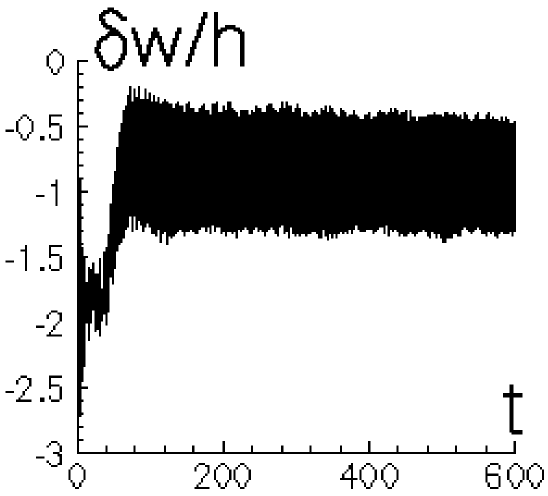


Frequency



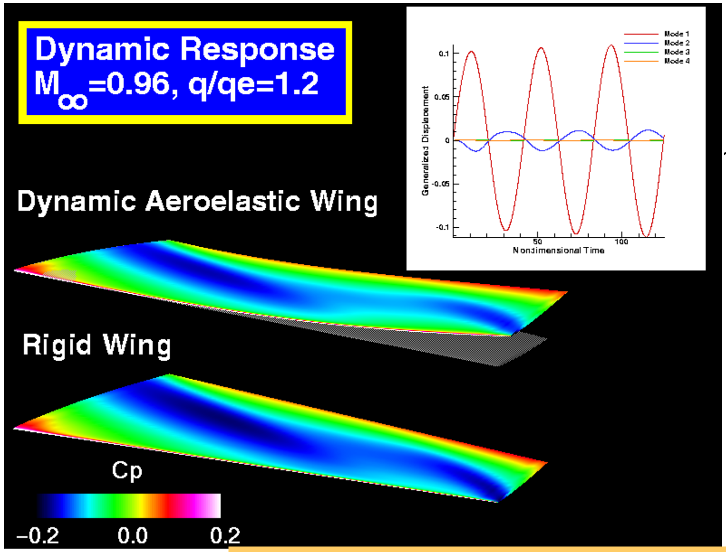
Nonlinear Fluid/Structure Interaction Computational Efficiency

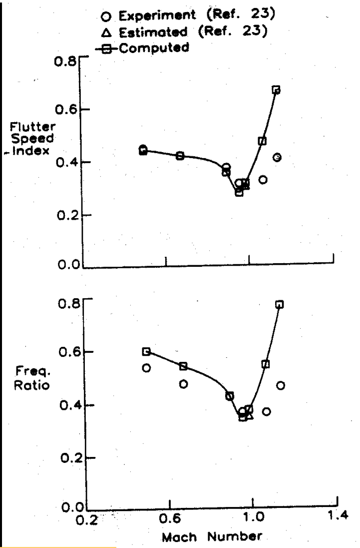




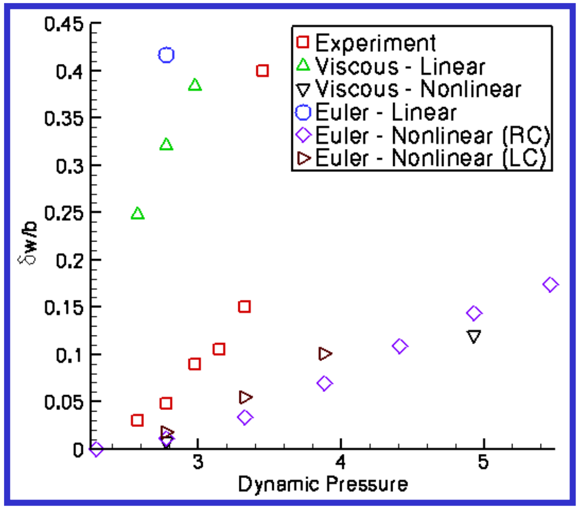
- Long time integrations may be required for nonlinear aeroelastic problems
- Physical considerations limits time step size
- Computational schemes need to be efficient to successfully compute such flows
- Are reduced order techniques(POD, Harmonic Balance, Volterra Series) able to address this issue and under what conditions

Aeroelastic Computation Validation





Agard 445.6 Wing (1963)

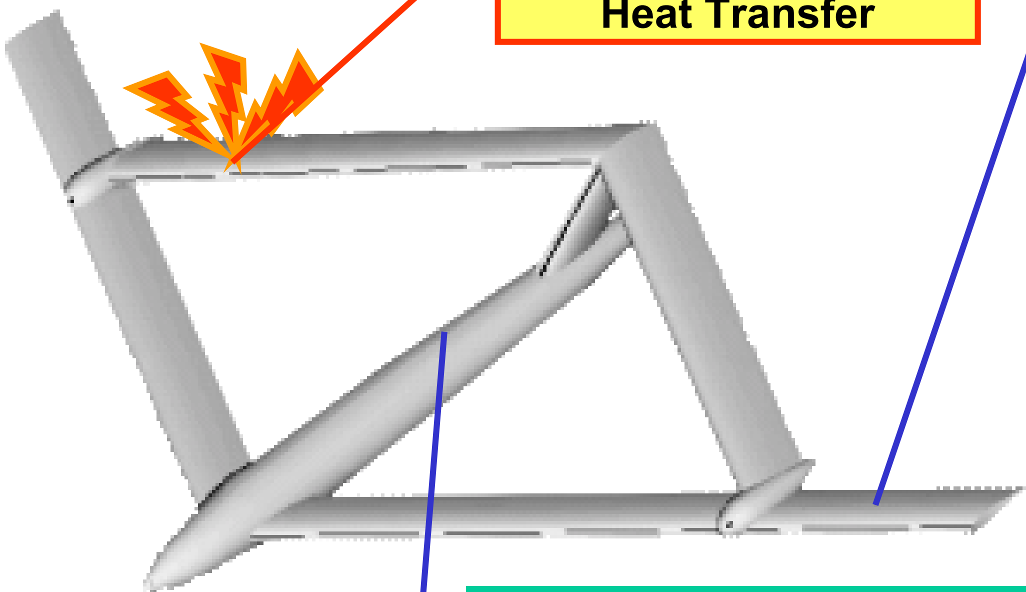


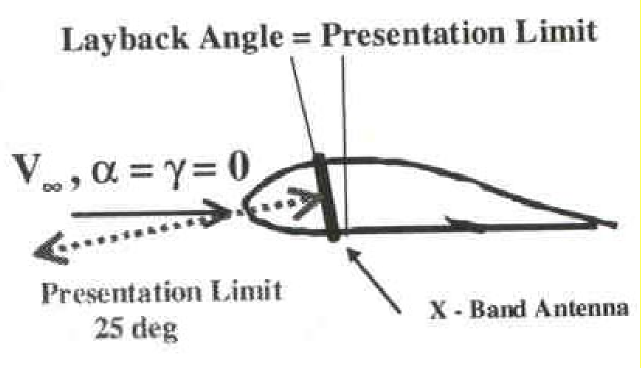
Cropped Delta Wing

- Need for well documented, basic fluid/structure interaction experiments for code validation
- Flow conditions for UAV type configurations may be challenging to reproduce
- New measurement techniques may need to be developed

Impact of Other Disciplines on the Fluid/Structure Interaction Problem

Thermal Management / Heat Transfer





Rigid Body Flutter – Flight Mechanics/ Structural Dynamics Interaction

UAV Design Issues may require the inclusion of <u>Multiple Disciplines</u>

- Heat Transfer
- Computational Electromagnetics
- Flight Mechanics

Key Issues

➢ High-fidelity computational aeroelastic methods are needed to address UAV fluid/structure interaction issues

- nonlinear in both fluid and structure models
- robust coupling and interface techniques
- temporal synchronization

➢ These schemes will need to be very efficient to address long temporal integration requirements

- Will reduced order models be capable of addressing this issue?

➢ Well documented, basic experiments are still needed for code validation

➢ Additional disciplines may need to be added to adequately address the fluid/structure interaction issues